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Effects of Changes in Arctic Lake and River Ice

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Abstract Climatic changes to freshwater ice in the Arctic are projected to produce a variety of effects on hydrologic, ecological, and socio-economic systems. Key hydrologic impacts include changes to low flows, lake evaporation regimes and water levels, and river-ice break-up severity and timing. The latter are of particular concern because of their effect on river geomorphology, vegetation, sediment and nutrient fluxes, and sustainment of riparian aquatic habitats. Changes in ice phenology will affect a wide range of related biological aspects of seasonality. Some changes are likely to be gradual, but others could be more abrupt as systems cross critical ecological thresholds. Transportation and hydroelectric production are two of the socio-economic sectors most vulnerable to change in freshwater-ice regimes. Ice roads will require expensive on-land replacements while hydroelectric operations will both benefit and be challenged. The ability to undertake some traditional harvesting methods will also be affected.

Keywords River ice · Lake ice · Climate · Arctic · Aquatic ecology · Northern development

INTRODUCTION

This manuscript is the third of three papers in this journal special issue (Callaghan et al. 2011) assessing the state and fate of freshwater ice in the Arctic. The material originates from the results of an international assessment of arctic lake and river ice conducted by the Arctic Monitoring and Assessment Program, SWIPA project (Snow, Water, Ice, Permafrost in the Arctic) (AMAP 2011). The first introductory manuscript (Prowse et al. 2011a [this issue]) provides details about its overall spatial extent, state of observation programs, and climatic role, while the second reviews the past and future changes in observed ice conditions and includes extensive On-line Supplementary Material about paleo-historical changes (Prowse et al. 2011b [this issue]). This article focuses on some of the key effects that changes in lake and river ice have had, or are projected to have, on freshwater ecological and socio-economic systems. Most of these, however, are also influenced by hydrologic impacts that are directly produced by changes in freshwater ice. The details and diversity of these are reviewed in the On-line Supplementary Material for this manuscript, which also contains a review of the chemical effects of changes to lentic and lotic ecosystems.

ECOLOGICAL EFFECTS

Lentic Ecosystems

The most critical climate thresholds for lake ecosystems are those affecting the area and volume of standing water, while changes in the ice regime and surrounding catchments can have major impacts on aquatic habitat size and integrity and geochemical inputs (Vincent and Laybourn-Parry 2008). In general, such changes are most apparent for relatively shallow systems, in some cases leading to their complete disappearance. For example, permafrost thawing and the production of surface to groundwater flow systems have been responsible for the elimination of many small water bodies in Siberia (Smith et al. 2005). Similarly, increased evaporative losses related to decreases in ice-cover duration can lead to the loss of aquatic habitats, such

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as the drying of High Arctic ponds (Smol and Douglas 2007). In other regions, the accelerated thawing of permafrost over the past 50 years has created new basins for lakes and ponds, and increased development of shallow-water ecosystems (Payette et al. 2004; Walter et al. 2006).

The surface area and depth of lakes and ponds affect ice formation. For example, lakes shallower than about 2-m regularly freeze to the bottom (i.e., lake ice typically forms to 2-m depth in most regions of the Arctic). Two possible consequences exist if the ice regime is altered. If winters become locally warmer and precipitation (as snow) increases, then ice thickness will decrease. Consequently, habitable depths for shallow lakes and ponds on tundra previously frozen to the bottom are likely to increase and enhanced invertebrate and/or fish survival may be possible. Another potential consequence will be a more rapid ice loss the following spring (related to a thinner ice cover) leading to an earlier open-water season and an earlier start to spring and summer production.

For some polar lakes, ice dams from glaciers or ice shelves are the primary structures retaining the freshwater, and their collapse can result in catastrophic drainage (e.g., Mueller et al. 2003; Vincent et al. 2009). The seasonal production and melting of ice dams along the Arctic coastline are responsible for stamukhi lakes, which are important biogeochemical processing sites for large river inputs to the Arctic Ocean that may be subject to climate-related impacts in the future (Galand et al. 2008).

Climate change is resulting in earlier dates of ice break-up (see Prowse et al. 2011b) and, for extreme High Arctic lakes, is causing the onset of summer ice-free conditions in lakes that in the past have been covered by perennial ice (Mueller et al. 2009; Vincent et al. 2009). Both snow and ice affect underwater ultraviolet (UV) radiation and photosynthetically available radiation. Model results suggested that reductions in snow cover would have a much greater effect on underwater UV exposure than moderate stratospheric ozone depletion (Vincent et al. 2007). In some ice-covered lakes, much of the photosynthetic production in the water column is associated with a deep maximum of phytoplankton or photosynthetic sulfur bacteria. In one high-Arctic lake, for example, past changes in planktonic production as inferred from pigment concentrations in sediments have been attributed to climate-related changes in snow and ice cover (Antoniades et al. 2009).

For some lakes, the loss of ice can result in the loss of vertical habitat structure and cooling (Vincent et al. 2008a). A further evaluation of potential future changes in water temperature and thermal lake structure across the Northern Hemisphere was conducted by Dibike et al. (2011). For example, Fig. 1 shows the mean annual cycle of simulated water-temperature profiles in hypothetical lakes of 20-m depth along longitudinal transects at 105°W and 90°E, representing cross-sections through central continental areas of North America and Asia, respectively. Results suggest that future warming will result in an overall increase in water temperature, with summer stratification starting earlier and extending later into the year.

Warming of the underlying water column by radiation is controlled to varying degrees by the thickness and composition of the snow- and lake-ice cover; white and black ice, for example, have different levels of albedo and transmissivity. In combination with water color and transparency, this affects heating rates, depths and mixing (e.g., Cahill et al. 2005). Earlier thinning and loss of ice cover also contribute to enhanced heating of the water column, which ultimately sets conditions for earlier and shallower development of the thermocline by increasing temperature differentials between surface and bottom waters. Longer open-water periods can further enhance overall lake warming, the combined effect being to drive high-latitude lakes from monomixis to dimixis. This threshold effect, as a result of water temperature rising above the point of maximum density (~4°C), can affect many other habitat properties, such as nutrient regimes and water-column oxygenation.

Ice is a key physical parameter that both structures and regulates abiotic and biotic processes within Arctic aquatic ecosystems. Biotic responses are induced at an individual, population, or community level depending upon the nature (rate, direction, magnitude, spatial scale) of abiotic change. Accordingly, shifts in ice characteristics will cascade through ecosystems, resulting in widespread alterations. For example, in addition to effects at the individual and population levels, changes in ice will affect trophic coupling, potentially engender mismatches between physical drivers and biotic responses, and affect phenological events such as the timing of key system transitions and life history shifts in biota.

In the case of photosynthetic production in lakes, the duration of open water is particularly critical. For example, the 250 000-year paleolimnological record from Lake El'gygytgyn, an ancient crater lake in the Siberian Arctic, showed that periods of the highest primary productivity were associated with warm, ice-free summer conditions, while the lowest rates were associated with periods of perennial ice coated by snow (Melles et al. 2007). In addition to improved light conditions for photosynthesis, measured levels of primary productivity could be further compounded by alterations in other environmental factors, such as increased wind-induced mixing and entrainment of nutrients into the euphotic zone, and catchment geochemical inputs.

Changes in the timing of freeze-up and break-up on lakes will also affect important biological aspects of seasonality. For example, the seasonal succession of plankton has been well described in many northern temperate lakes and is

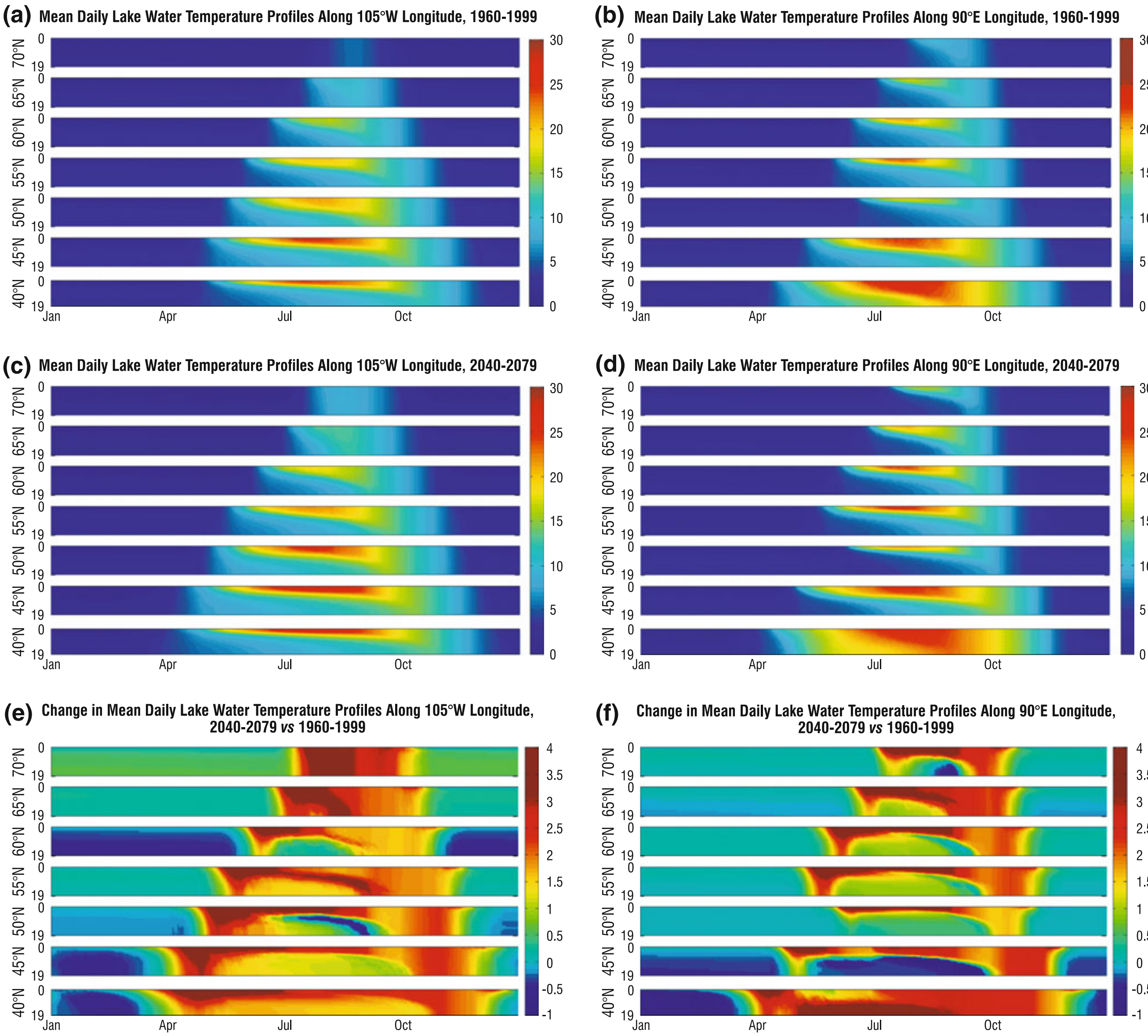

Fig. 1 Modeled mean annual cycle of daily profiles in water temperature in lakes during 1960–1999 (**a**, **b**) and 2040–2079 (**c**, **d**) as well as the corresponding change between these periods (**e**, **f**) at 5° latitude intervals along example longitudinal transects on (**a**, **c**, **e**) 105°W and (**b**, **d**, **f**) 90°E. *Source* Dibike et al. (2011)

strongly coupled with the freeze-up and break-up of ice cover and summer thermal stratification (Sommer 1989). A variety of structural and functional ecosystem changes in such lakes have been coupled to the changes in seasonality, in particular to an earlier ice break-up and an earlier onset of stratification, and provide insights into how Arctic lakes may respond to ice-induced changes in seasonality. One of the most obvious effects of an earlier timing of temperate lake-ice break-up has been an advanced spring phytoplankton bloom (e.g., Peeters et al. 2007) often resulting in an earlier zooplankton biomass peak. However, a synchronous response to these higher spring temperatures is usually restricted to fast-growing plankton, while slow-growing species with complex life histories show species-specific responses (e.g., Adrian et al. 2006).

Changes in lake-ice regimes will have significant impacts on primary productivity and related trophic relationships in Arctic lakes. For example, increased temperatures and stratification associated with decreases in ice cover, accompanied by larger nutrient inputs, may favor the development of certain phytoplankton. In the case of noxious blooms of cyanobacteria, this could be a significant concern. Seasonality of the plankton is also likely to be affected by temporal changes in ice coverage given that planktonic flagellates have been observed to be abundant below the ice in Arctic lakes, whereas diatoms appear once the ice has gone. In general, although photosynthesis does take place beneath an ice cover, it is expected that primary production will increase with decreased ice thickness and snow cover (e.g., Vincent et al. 2008b). However, in Arctic regions projected to experience increases in surface accumulations of snow and/or the formation of white ice, under-ice plankton abundance could be negatively affected. Such changes in snow and white-ice coverage are also likely to affect levels of secondary productivity. Fish production in northern alpine lakes, for example, has been linked to snow depth (Borgstrøm and Museth 2005; Prowse et al. 2007).

Changes in water-column stratification associated with increased duration of open water can potentially result in the loss of some species and the establishment of others. By contrast, increased open water can allow the development of new trophic levels and even the establishment of aquatic bird species (Vincent et al. 2009). Warmer, more nutrient-rich dimictic conditions may also favor cladocerans (Sorvari et al. 2002). Importantly, this could result in increased bioaccumulation of methylmercury relative to copepod-dominated zooplankton communities (Chételat and Amyot 2009), with the potential for increased mercury transfer to fish and humans, although effects of biodilution may counteract this effect (Gantner et al. 2010).

Depending upon latitude, as well as specific lake characteristics, early thermocline development will profoundly alter lake ecosystems as well as the cold-water fish species present. Using lake trout in North America with summer temperature preferences of 10–12°C as an example, under climate warming southern boreal lakes will experience earlier and perhaps deeper thermocline formation than at present. Accordingly, the metalimnion (middle layer of a thermally stratified lake) and hypolimnion (lower layer of a thermally stratified lake) volumes will be smaller. These areas are used as a summer thermal refuge by lake trout (*Salvelinus namaycush*) at southern latitudes to escape epilimnion (upper mixed layer of a lake) temperatures of more than 12°C; thus, smaller volumes of preferred habitat will lead to stress for individuals. At least over the near future, suitable thermal habitats for lake trout in Arctic lakes are likely to remain similar to those at present or increase in volume, thus promoting lake trout growth (provided that all other factors are equal).

The effects of wind are a complicating factor in ice dynamics and thermal structure affecting habitats. Earlier ice loss results in larger fetches being open earlier and longer. Wind-driven mixing of surface waters will almost certainly interact with heating to complicate thermocline development and depth; however, the nature of such effects remains unclear. Given that lake trout are generally long-lived, such climate change signals may not be readily discernible within the populations. Moreover, decreased occurrences of winter fish kills due to oxygen depletion events will generally be an additional effect of reduced ice-cover duration (Stefan and Fang 1997). However, the significance of this is likely to vary by latitude and lake characteristics.

Ice cover also affects the migration and dispersal of aquatic organisms. A small number of Arctic lakes are permanently ice-covered (e.g., Vincent et al. 2008a) and their summer melt-out is typically restricted to a narrow moat. This greatly limits the wind-induced mixing and the presence of some biota. Increased melting of ice and snow in both the catchment and lakes in a warmer climate may result in an increased overflow and, consequently, a greater hydrological connectivity between the lakes (Kusumastuti et al. 2008).

Lotic Ecosystems

In Arctic rivers, ice is important in defining the in-stream habitat for fish, invertebrates, and aquatic plants. Through the modifications of ice regimes, climate change will have a profound influence on the behavior and biological response of stream biota (Huusko et al. 2007) and, therefore, will play a central role in their growth, survival and reproduction. Surface ice creates shelter habitats for fish in areas that are too exposed for use during open-water periods (Stickler et al. 2007; Linnansaari et al. 2009). A reduction in such ice shelter will, therefore, lead to a loss of suitable winter habitat during the period when the water temperature has not yet reached the level to cause changes in fish habitat use. In small and steep streams, winter formation of ice will define habitat availability and distribution independently of changes in discharge (Stickler et al. 2010). In such environments, a shorter ice season will influence habitat diversity. In addition, with future climate warming, an increased number of winter warm spells leading to mid-winter ice break-up may have a significant influence on habitat availability. Many Arctic rivers that currently have bed-fast ice, and thereby no available winter habitat, may shift into a regime with a floating ice cover. This will create new habitat for winter survival of species in these rivers.

Changes in ice cover can also have a direct impact on fish productivity and mortality. For example, for Atlantic salmon (*Salmo salar*) adapted to complete ice cover, removal of an ice cover has been shown to produce significant negative effects on their energy budget (Finstad et al. 2004a). Energy deficiency is important to winter survival, and a change in ice cover can reduce their ability to survive winter (Finstad et al. 2004b). Movement of salmonids to overwintering habitats mostly occurs prior to ice formation in rivers; however, local movements between habitats also occur after ice formation (Jakober et al. 1998; Linnansaari et al. 2009). Extensive anchor ice precludes access, whereas patchy anchor ice and ice-covered areas appear to be preferred (Linnansaari et al. 2009). Accordingly, reduced ice cover or duration on river systems is likely to result in a tradeoff between increased habitat (or access to such) with that habitat being less preferred due to lack of surface ice cover. Access, primarily by migratory *Anadromous salmonids*, to key overwintering habitats may thus provide benefits to overall population survival and productivity.

Large-scale changes in ice-cover duration and break-up timing will alter flow regimes and thereby influence Arctic rivers as migratory routes, affecting the timing of fish runs or even the migration of large mammals such as caribou (Sharma et al. 2009). Changes in flow timing in spring will also impact conditions for fish out-migration (Reist et al. 2006a, b). The loss of an ice cover is likely to increase the risk of predation on stream-living animals from mammalian and avian predators due to the loss of critical in-stream shelter. Moreover, winter and related ice formation could act as a 'bottleneck' for survival of fish and invertebrates. Results reported by Huusko et al. (2007) suggest that the variability in creating such bottlenecks among rivers is highly context dependent and controlled by the life stage of the fish, local habitat, and the related type of ice regime. Overall, the large and complex scope of potential changes in future river-ice regimes will make predictions of future biological responses difficult, particularly considering the current rather limited knowledge of high-latitude lotic systems.

River Delta Ecosystems

A number of major river deltas are found along the Arctic coast, as well as on the rivers that drain into the Arctic Ocean. It has been recognized for some time that the water budget and nutrient-sediment supply of delta riparian zones are heavily dependent on ice-jam floodwaters. The strength of this dependence has been reinforced by recent work on the Mackenzie River delta, which contains about 45 000 riparian lakes. Specifically, decreases in the severity of river-ice break-up has lessened the flooding of high closure lakes, which has the potential to result in the loss of some of these water bodies and changes in the biogeochemical processing of river water by the floodplain ecosystem (Fig. 2) (Lesack and Marsh 2007). Future climate conditions that produce thinner ice and reduced spring runoff (due to a smaller winter snowpack) will lead to overall reductions in ice-jam flooding (Beltaos et al. 2006) and could increase the threat to the health of such riparian ecosystems.

Freshwater environments at the coast are also prone to the effects of changing ice conditions. In the High Arctic, for example, fjords can be blocked by thick multi-year sea ice and ancient ice shelves, resulting in an extensive layer of freshwater called an 'epishelf lake.' These environments are proving to host microbial ecosystems with diverse biological communities; however, they are extremely vulnerable to ongoing climate warming and the loss of ice. Observations along the northern coastline of Ellesmere Island, Canada, have shown that many of these unique ecosystems have been driven to extinction as a result of recent climate change, and that they are sensitive indicators of climate change (Veillette et al. 2008). Other ice-dependent freshwater lakes at the High Arctic coast are becoming inundated with seawater due to the loss of integrity of their retaining ice dams (e.g., Vincent et al. 2009), and the extensive, microbiologically rich ice-bound lakes on ice shelves are disappearing completely as a result of their melting and collapse (Mueller et al. 2008).

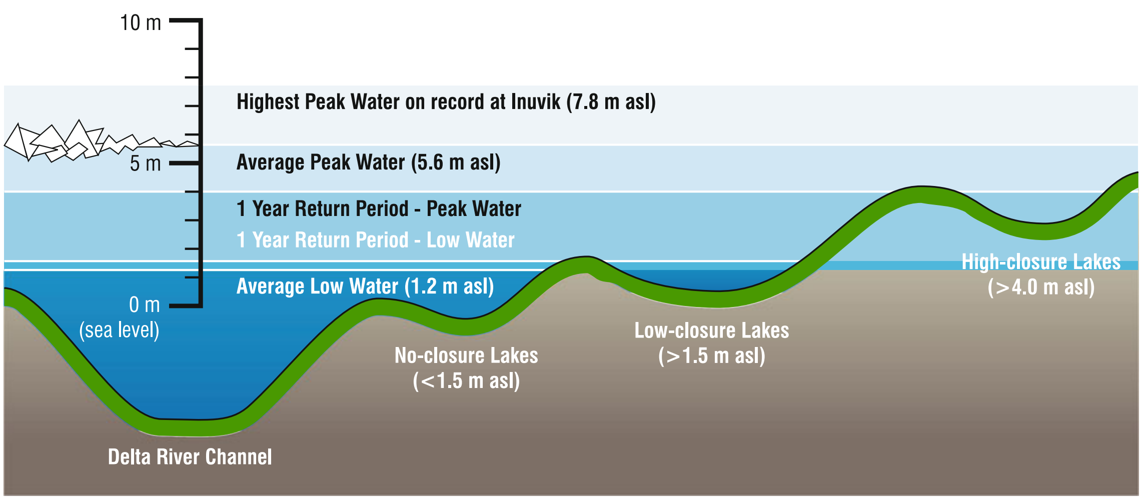

Fig. 2 Classification of lakes in the Mackenzie River delta according to the extent of their isolation from the river. Ice-jam floodwaters are responsible for flooding of the riparian lake systems more hydraulically unconnected to the main flow system. Modified from Emmerton et al. (2007)

SOCIO-ECONOMIC CONSEQUENCES AND ADAPTATION OPTIONS

Northern Infrastructure, Transportation, and Traditional Lifestyles

Lake and river ice provide seasonal transportation platforms throughout the Arctic. Many northerners depend on this natural network for access to isolated communities, remote industrial developments and, hunting, fishing, herding and trapping areas, often in support of traditional subsistence-based lifestyles (e.g., Vuglinsky and Gronskaya 2006; Prowse et al. 2009). Changes in ice regimes, however, will make such access more uncertain and potentially hazardous and may reduce the ability to undertake some traditional harvesting methods. By contrast, any increase in the ice-free season will reduce the costs of ice breaking to maintain shipping routes, such as on the Yenisey River where nuclear-powered ice breakers are currently used.

Although scientific publications that explicitly detail the importance of ice roads to northern communities are rare (e.g., Ford et al. 2008), there are many accounts in the public press when such networks are affected by unseasonably warm weather. In one event reported by Carlson (2010), mild weather in March 2010 caused the province of Manitoba, Canada, to close a 2200-km winter road network composed of muskeg, lakes, and rivers. It had deteriorated to the point of stranding numerous freight haulers and local drivers, necessitating emergency evacuations. Typically, the road carries more than 2500 shipments each year to more than 30 000 first nations people. In response to dwindling construction supplies, rising food and fuel prices, and a related rise in unemployment, First Nations Chiefs declared a state of emergency in 11 communities. Carlson (2010) also noted that because of deteriorating conditions, approximately 600 km of the winter road system have been relocated to land since 2001 (Government of Manitoba 2010) and spending on winter roads has tripled since 1999 (Government of Manitoba 2009).

Ice roads are also critical to the resupply of the complex of mining centers, which cannot use air access for the transport of heavy loads, fuel, and large equipment. One example is the 600-km long Tibbitt to Contwoyto Winter Road in northern Canada, which travels over 495 km of frozen tundra, lakes, and rivers (Fig. 3). It has been estimated to contribute significantly to the territorial and national annual economies—approximately US$ 800 million and US$ 350 million, respectively, in 2001 but rising significantly with enhanced northern development (EBA Engineering Consultants 2001). A similar example is the 360-km long winter road in the Chukotka region of Russia constructed each winter from the ocean port Pevek to the Kupol gold and silver mine at Bilibino (Noble 2009). In such cases, reductions in ice duration, thickness, or mechanical strength could have major implications for such remote developments. For some Arctic centers, changes in ice-related transport can have both positive and negative effects. In the case of Arkhangelsk on the Northern Dvina River, Russia, an increased shipping period and freight turnover from the inland navigation fleet would result from a decrease in ice duration, but, on the other hand, delays in the building of ice-road crossings would create substantial difficulties for local freight and public transportation (Ginzburg 1989).

Initially, adaptation to the reduction in the size of maximum loads that can be safely transported on northern ice roads could involve (i) modifications to techniques involved in ice-road construction; or (ii) modification of transport schedules to concentrate more on the coldest part of winter (Prowse et al. 2009). Continued warming will preclude ice roads as a major form of northern transportation, and there will be a need for alternative forms of transportation. In cases where an open-water network is feasible, transport by barge could be possible. For land-locked locations, however, the only viable option for heavy-load transport will be the construction of land-based road or rail networks. The initial capital costs of these, however, are likely to be enormous, especially where they must pass over terrain that is also projected to experience significant permafrost thaw and subsidence from climate change.

Hydroelectric Power

Production of hydroelectric power is important in several Arctic countries, the operations of which are seasonally constrained by the effects of river ice. At present, the total installed capacity in the Arctic countries (2006 data) is approximately 80 GW (Fig. 4), but for many areas, unregulated large northern rivers still hold vast potential (Prowse 2009). With the future projections of inflow, this potential will probably increase for most of the Arctic region (Hamududu and Killingtveit 2010). Changes in ice conditions can affect hydroelectric operations in a number of ways, both positively and negatively. For example, the estimation of ice loads on facilities such as dams, intakes, outlets, and gates is important both for engineering design and operations (Comfort et al. 2003). A shorter ice season and thinner ice cover could reduce the static ice loads on dams, but on the other hand, a more unstable winter with mechanical ice break-ups could increase the dynamic loads on in-channel facilities. More unstable winter conditions could also lead to weakened ice and consequently a reduction in ice loads.

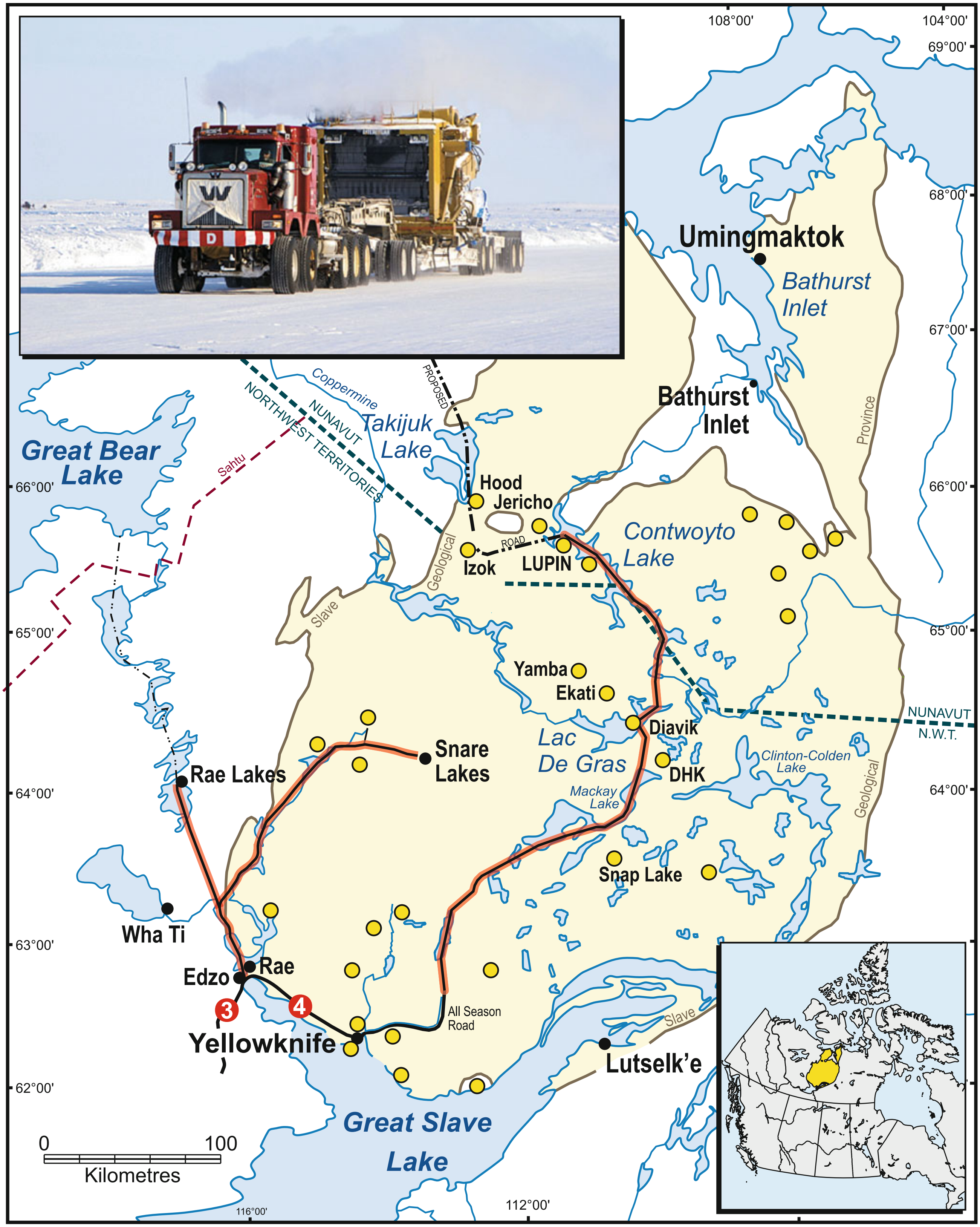

Fig. 3 Example of large loads transported on the Tibbitt to Contwoyto Winter Road in northern Canada, which is composed of many long reaches across frozen tundra, lakes, and rivers. Photo courtesy of Joint Venture Management Committee, partnership between DeBeers Canada, Inc.; BHP Billiton, Ltd; and Diavik Diamond Mines, Inc

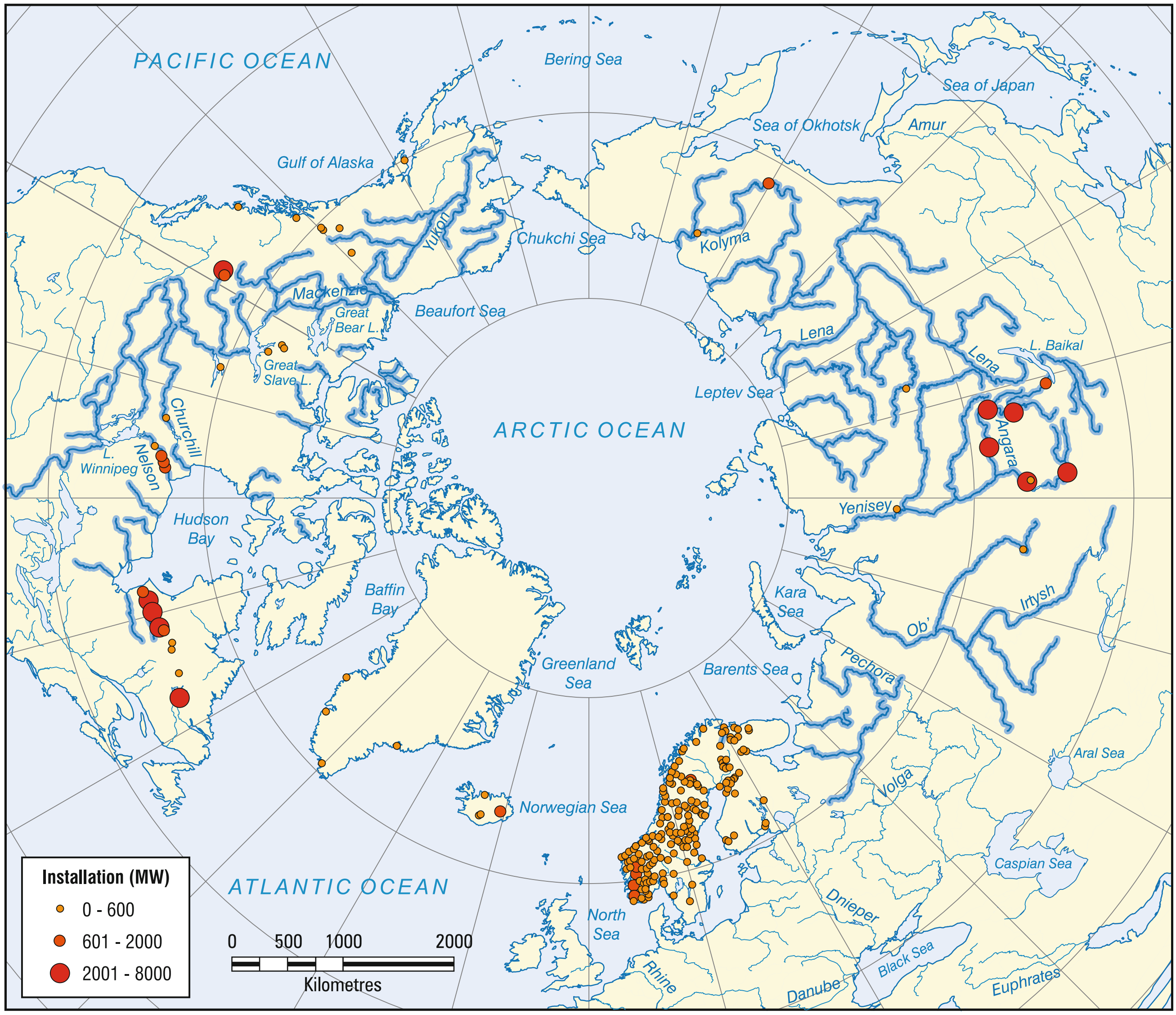

Fig. 4 Location and size of major hydroelectric facilities located in ice-dominated river regimes of the circumpolar North. All such stations will require major modifications to current operational regimes and possibly infrastructure modifications based on projected changes to freshwater ice regimes (due to data availability, the figure may not show all existing plants). *Source* K. Alfredsen, Norwegian University of Science and Technology

Some of the most costly ice-induced effects on hydroelectric production are caused by ice blockages, which typically result from two sources, both of which could be altered by future ice regimes. First, the intensity and magnitude of frazil ice formation is projected to increase or decrease depending on relative changes in autumn air temperature and flow regimes compared to current climatic conditions (Beltaos and Prowse 2009). While decreases in frazil ice production will ease constraints on hydropower production, increases can cause blocking of trash racks and intake structures (Ettema et al. 2009), thereby reducing production and increasing operational costs. Moreover, it could also initiate ice problems in downstream river reaches as inflowing production water is forced to bypass intakes. Reaches downstream of intakes are usually characterized by early ice formation and low winter-flow, and sudden releases of water may initiate mechanical break-ups, resulting in ice jamming and erosion damage. In a future with less stable conditions and a longer freeze-up period, this problem may increase in some areas, but it is also likely that it will be reduced in the most southern, temperate river systems. Second, in regions where there is an increase in the intensity or frequency of mid-winter warming spells and, therefore, an increased potential for mechanical winter break-ups, clogging of intakes by drifting ice will cause a loss of water, thus decreasing production. This will be a problem particularly for secondary intakes used in water transfer in high-head systems (Lokna 2006). Monitoring and mitigation of such problems will be an issue especially for hydropower producers with remote facilities. Although hydropower dams are equipped with spillways to pass floods, the function of which is crucial to dam safety, ice formation can have an impact on the capacity and functionality of these structures (Lia 1997). In a period with more frequent mid-winter ice break-ups, spillway functionality may be affected, particularly in spillway systems with tunnels or gates.

The strength of ice on hydropower impoundments is strongly influenced by reservoir operations such as the lowering of water levels during winter. In a future with shorter winters and a thinner ice cover, the safety of using reservoir ice for transportation may be compromised. However, such changes in reservoir ice conditions could also lead to some positive impacts for reservoir design and management. Future climate conditions will decrease this volume of inactive storage and reduce some of the current negative consequences, including (i) part of the storage volume being unavailable during winter when electricity demand is high; (ii) grounded ice having the same effect as an additional dead pool storage, forcing the design of larger and costlier structures; (iii) the immobilized water only becoming available at the end of winter when streamflows are large (and demand for electricity is low) thereby increasing flood risk and the probability of spilling; and (iv) grounded ice changing the effective storage curve during winter, which if unaccounted for in dam operations leads to suboptimal decisions (Seidou et al. 2007). Reductions in any or all of these will provide benefits to hydroelectric operations.

The importance of river ice on hydroelectric operations may also be indirectly affected by future energy adaptations. For example, a reduction in greenhouse gas emissions will require the production of more renewable energy and lead to the introduction of more non-storable energy sources. In such a system, load balancing is needed to maintain a continuous supply, and hydropower is ideally suited for this (e.g., Benitez et al. 2008). This will have implications for the operational strategies of hydropower producers toward a peaking schedule, and must be considered when impacts of changes in river ice are evaluated. Generally, peaking operation of hydropower plants in rivers is considered an environmental challenge, and peaking during the ice season further increases potential problems (Scruton et al. 2008). Balancing the variable production from non-storable renewables could lead to a less regular operation of the hydropower system, thereby increasing the potential problems linked to break-up and ice jamming in rivers downstream of hydropower outlets.

CONCLUSIONS AND FUTURE RECOMMENDATIONS

A cascading set of hydrological, ecological, and socio-economic effects have been, or are projected to be, caused by climatic related changes to lake and river ice. Of particular concern to hydrologic regimes are alterations to river low flows, lake evaporation and water levels, and river-ice break-up severity and timing. River geomorphology, vegetation regimes, and nutrient/sediment fluxes that sustain aquatic ecosystems are particularly sensitive to changes in the latter. Changes in river ice are also likely to have wide-ranging effects (both positive and negative) on the behavior and biological response of stream biota. With respect to lakes, changes in the timing of freeze-up and break-up will affect a wide range of related biological aspects of seasonality. Some changes are likely to be gradual, but others are likely to be more abrupt as systems cross critical ecological thresholds. Once again, positive and negative effects are possible. Changes in ice-induced hydrological connectivity and lake stratification also could lead to the loss of some species and the establishment of others.

Transportation and hydroelectric production are the two socio-economic sectors most vulnerable to change in freshwater-ice regimes. Continued warming will preclude ice roads as a major form of northern transportation; alternative forms of transportation will therefore be needed, but the capital costs of these are likely to be enormous. Changes to ice regimes will also make the practice of some traditional subsistence-based lifestyles potentially hazardous and may reduce the ability to undertake some traditional harvesting methods. Hydroelectric operations will both benefit and be challenged by changes in river-ice conditions. Monitoring and mitigation of ice-related problems will be a particular issue for hydropower producers with remote facilities.

Advancing the understanding of climate-induced changes to Arctic freshwater ice and the subsequent effects will require improvements to monitoring, predictive modeling, and assessments of adaption options. Monitoring around the circumpolar North could be greatly assisted by a standardization of in situ observation methods to facilitate intercomparison of data. Given the remoteness of much of the high latitudes, a special focus should be placed on adopting remote sensing approaches to augment the in situ networks. To achieve improved prediction of river-ice regimes, advancements need to be made in integrated models that consider future combined changes to landscape hydrology, water-ice-air energy exchanges, in-stream hydraulics, and ice mechanics. Associated predictive modeling of lake- and river-ice systems should be expanded from primarily physical characteristics to include effects on lentic and lotic ecosystems. A number of "supersites" from representative regions should also be established around the circumpolar North for conducting long-term monitoring, intercomparison of observational techniques, and validation of modeling results. Given the importance of many ice-affected socio-economic sectors in the Arctic, key locations of such activities should be considered in the selection of such supersites. By doing so, it is likely to maximize the socio-economic benefits of conducting future freshwater ice and climate change research in the Arctic.

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